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MHD PLANT TURN DOWN CONSIDERATIONS

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ABSTRACT

The topic of part load operation of the MHD power plant is assessed. Current and future planned MHD research is reviewed in terms of addressing topping and bottoming cycle integration needs. The response of the MHD generator to turn up and down scenarios is reviewed. The concept of tuning the MHD power to met changes in plant load is discussed. The need for new ideas and focused research to study MHD plant integration and problems of plant turn down and up is cited.

INTRODUCTION

Commercial central power stations must have the capability of plant turn up/down to meet system demands. This need will continue to hold true for the MHD power plant and the best means for achieving this with the MHD generator topping cycle is at present uncertain. Although the turn down requirements for the MHD power plant is an issue which has been apparent for years, it is one that is largely being bypassed in contemporary experimental MHD research.

Consumer power demands vary with the seasons of the year and on a weekly, even daily basis. The MHD plant needs to be flexible enough to respond to both types of demand. Seasonal power changes are sustained periods of plant turn up/down around its design point. This part load criteria is that around which the design point of the plant as a whole revolves and the criteria by which the design of the MHD topping cycle can be judged. Rapid changes in plant output are required to meet daily power demands changes that occur with peak/off-peak consumption periods. When these are excessive, auxiliary power is brought on-line. The MHD power plant offers an attractive alternative to enhance the plant's power response. Within a range that proves both efficient and economical, immediate power changes may be met by "tuning" of the MHD cycle. Tuning of the MHD generator can produce rapid power transients with a minimum disruption of normal plant operations. For both the turn up and turn down scenario, one principal unknown at this time is the off design capability of the MHD topping cycle. The range of operation that the MHD system must exhibit around its design point in an combined cycle has never been clearly established.

A corollary to the turn up/down limitation of the MHD plant is also of interest. That is, what design modifications are possible which could extend this capability? The topping cycle design is fixed by its working fluid and geometry. It is reasonable to consider alternatives to this approach when looking farther into the future toward advanced MHD power plant systems.

MHD Power Research

The current Department of Energy (DOE) sponsored MHD research is structured around experimental demonstrations at two major test facilities [1]. The Component Development and Integration Facility (CDIF) is to conduct Proof-of-Concept (POC) tests with hardware and components of the MHD topping cycle. The current phase of this research, designated the Integrated Topping Cycle program, will conduct long duration, reliability tests of 50 MWt scale, prototypical topping cycle components.

The second DOE test facility is the Coal-Fired Flow Facility (CFFF) located at The University of Tennessee Space Institute (UTSI). This facility is a pilot scale (20 MWt) experimental test train that includes MHD bottoming cycle Heat Recovery and Seed Recovery (HRSR) equipment. The CFFF research is directed at long duration POC tests of bottoming cycle components. This research encompasses studies that are critical to the successful commercialization of MHD power, such as, seed (potassium) recovery, fouling, and control of emissions.

Independent experiments at these facilities are being conducted simultaneously. The research objectives of both are common and center around study of the physics of MHD power processes and demonstrations of long term component reliability. Emphasis is placed upon the latter since hardware reliability is an issue that can be verified on an experimental scale.

Table I compares the two DOE MHD research facilities and two MHD retrofit concepts. The operating points for the two research facilities have evolved from the results of past research in each. There is a notable difference in the scale and test trains of these two facilities. The CDIF operates with nearly three times the throughput of the CFFF. The coal combustors are

TABLE I
Operating-Primary Combustion Specifications

CFFF : Thermal Input (Coal and Oil (50:50) ~ 20 MWt\
Stoichiometry ~ 0.85
Oxygen Enrichment (N/O molar) ~ 1.14
Seed Fraction ~0.8 %K (K_2/S = 1.1)
Throughput ~ 2.82 kg/s

CDIF: Thermal Input (Pulverized Coal) ~ 50MWt\
Stoichiometry ~ 1.0
Oxygen Enrichment (N/O molar) ~ 0.7
Seed Fraction ~1.5 %K (K_2/S = 3.1)
Throughput ~ 8.3 kg/s

Scholz MHD Retrofit [2]
Thermal Input (Coal - High Sulfur) ~ 190 MWt\
Stoichiometry ~ 0.88
Oxygen Enrichment ~ 40% (by Volume)
Seed Fraction ~1.8 %K (K_2/S = 1.0)
Throughput ~ 36.5 kg/s

Corette MHD Retrofit [3]
Thermal (Coal - Low Sulfur) ~ 250 MWt\
Stoichiometry ~ 0.90
Oxygen Enrichment ~ 38% (by Volume)
Seed Fraction ~1.0 %K (K_2/S = 2.1)
Throughput ~ 114.0 kg/s

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markedly different in design and size. The large CDIF slag rejecting combustor uses a two stage coal burning process to remove around 50% of the slag from the combustion plasma. The CFFF coal combustor is a compact, single stage unit that exhausts directly into the test train.

In the CDIF, where the MHD generator is the key component being researched, the combustion point used is that which enhances the MHD power generated in that system. This enhancement assures simulation of the generator electrical performance, in particular, the electrical stress. Long term reliability of the generator under electrical stress is a key MHD R&D issue. The CFFF simulates coal combustion with preheated air by burning a mixture of coal and fuel oil. The lower stoichiometry operating point is that determined as optimum for control of nitrous oxide emissions from that system.

The difference in operation of the two test facilities may appear contradictory to the needs of obtaining information on integration of the MHD and steam cycles. From the standpoint of the thermodynamic processes this is true. However, the distinctly different operation for the two test beds are acceptable at this stage of applied MHD component research. The need to develop individual components for the MHD plant is the overriding force that directs POC research. This need is pressing, however, at the same time the results of this research must consider the big picture of plant integration. Final hardware specifications for the commercial MHD plant will inevitably be influenced by the need to smoothly integrate the two cycles. It is reasonable to project that plant controls and even the physical design of major components will be influenced by the power station needs.

The next major step after POC testing in the research plan for development of MHD power is that cited in Table I as MHD retrofit. This step is that in which cycle integration problems will first be experimentally addressed.

DISCUSSIONS

MHD plant turn up/down has underlying issues which should be understood prior to attempting an integration of the MHD topping and steam bottoming cycles on a large scale. These issues stem from the desire to optimize plant part load operation from the standpoints of plant dynamics and overall efficiency. Most technical problems that are associated with part load operation evolve from the differences in the thermodynamic processes of the MHD plant's topping and bottoming cycles. The MHD generator process demands a high temperature (>2500K), high velocity (~1000 m/s) working fluid stream. The heat transfer processes which drive operation of the steam plant are more thermodynamically relaxed. Whereas, the MHD cycle output will exhibit a near instantaneous response to changes in plant operations, the time scale for the steady state output response of the steam cycle is on the order of hours at the minimum.

The issue of turn up/down is a question of the overall plant efficiency breakeven point. The MHD system with fixed geometry is optimum at only one operating point. Consequently, the MHD plant can be expected to maintain greater conversion efficiency than the conventional steam plant only within a range of operation around the topping cycle design point. If turn up/down demands operation outside of this range, the MHD advantage may disappear.

Typical load demands for a large scale central power plant are shown in Figure 1.[4] Figure 1 gives the 1990 seasonal projections for power plant loads up to 1100 MWe. A turn down ratio greater than 20% peak load is anticipated. These projections have been normalized for peak load, cast into terms of overall plant efficiency and replotted in Figure 1. The results of this exercise typify the relative reduction in efficiency with turn down for a large coal-fired steam plant.

A near equal split in output power between the MHD and steam cycles is projected for a commercial MHD plant of the scale of that given in Figure 1. The overall efficiency of the combined cycle plant is expressed according to:

$$\eta_{overall} = \frac{P_{MHD} + P_{stm} - P_{aux}}{Q_{th}}$$

where P_{MHD} is the MHD power, P_{stm} the power from the steam cycle, P_{aux} is all auxiliary power demands, and Q_{th} the total thermal input. The overall efficiency is functionally dependent upon both the MHD cycle and steam cycle.

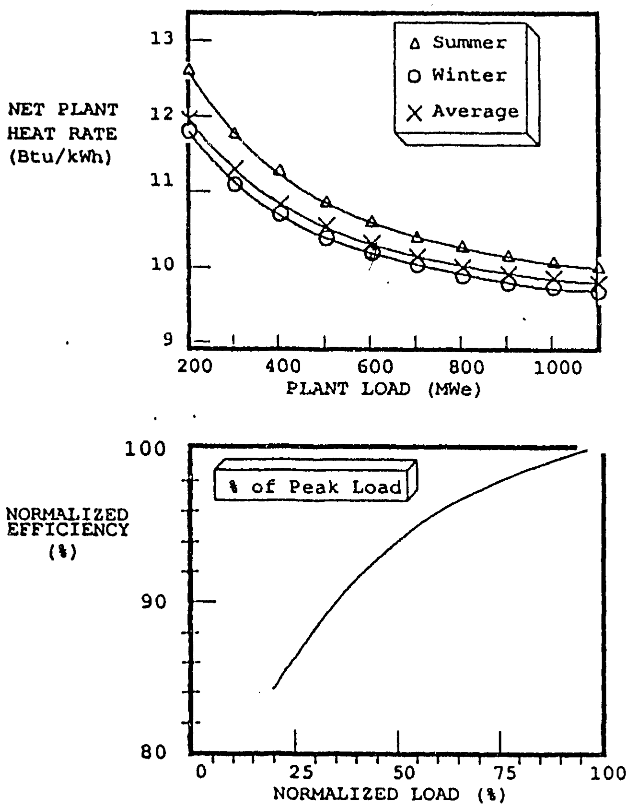

Figure 1. Steam Plant Turn Up/Down Demand [5]

These efficiencies are coupled through plant interfaces, i.e., feedwater and compressor power.

The efficiency of the MHD generator is defined by enthalpy extraction,

$$\eta_{ee} = \frac{P_{MHD}}{Q_{th}}$$

whereas,

$$\eta_{MHD} = \frac{P'_{MHD}}{Q_{th}}$$

for the entire topping cycle, P'_{MHD} is net power output accounting for auxiliary power needs of the MHD cycle. Major inefficiencies unique to MHD include compressor power, oxygen plant power, magnet power (cryogenic processing), power conditioning losses, and heat losses. Of these, the compressor power and wall losses will be most affected by plant turn up/down. Compressor power increases with throughput, wall losses increase with flow Reynolds number and temperature.

No comprehensive study of MHD plant part load operation for a specified plant was uncovered. in literature Most work to-date has concentrated on defining an MHD plant design rather than analyzing part load operation of a given one. Past works size the MHD topping cycle as optimum to fit a specific plant type and design point. What needs to be addressed in new studies is the combined cycle performance for a fixed MHD plant design.

Turn Up/Down of the MHD Cycle

Some basic information on turn up/down of the MHD plant can be derived by considering the MHD topping cycle from a general scaling point-of-view. That is, what response in terms of MHD power and efficiency can be anticipated when plant operation is perturbated around its design point? And, what are the limitations on just how much operation can be "tuned"?

Combustion. To achieve turn up/down capability where only a small change in plant output is needed, variations in the MHD electrical output can be achieved by operator enforced control over the combustion process. Changes in the reactant mixture varies the electrophysical quality of the plasma. Three key combustion controls that are available to the plant operator are: stoichiometry, oxygen enrichment, or seed flowrate. Combustion control offers a possible means for immediate control over the MHD cycle but has limited range.

Limits exist on the stoichiometry range and N/O that can be used in plant operations to control nitrous oxide (NOx) production. CFFF experience has shown that to control stack (NOx) emissions below projected EPA standards requires substoichiometric combustion. A commercial size system will be similarly regulated - a conclusion reached by Chapman in study of the mature MHD plant.[5]

Plasma conductivity can be varied by changing seed fraction. The MHD process requires around one percent potassium in the total flow. Increasing seeding level yields little change in conductivity; however, a substantial conductivity reduction can be achieved by reducing seed. Within a range, this can be accomplished without compromising plant efficiency. Experience has shown that control over sulfur emissions requires maintaining potassium content in the flue gases at adequate scrubbing levels. And, carbonate fouling of downstream heat exchanger surfaces becomes severe when the ratio of potassium to sulfur (K_2/S) is too high. Thus, a limiting range in seed level exists as dictated by the performance of the overall plant, dependent upon coal sulfur content .

Figure 2 is a plot of the variation in K_2/S with seed fraction. Two features are noticeable. First, low sulfur coals require high K_2/S to achieve needed seed fraction (1%). Addition of sulfur (K_2SO_4) to the combustion process has been suggested as a means to minimize carbonate fouling. Secondly, for high sulfur coals the turn down in seed fraction is limited by the need to maintain at least a K_2/S of one. Consequently, the bottoming cycle places restrictions on just how much the seed percentage can be reduced to tune power in the MHD cycle. Large turn down of seed fraction for coals with high sulfur content (e.g., Eastern coal) may not be permissible.

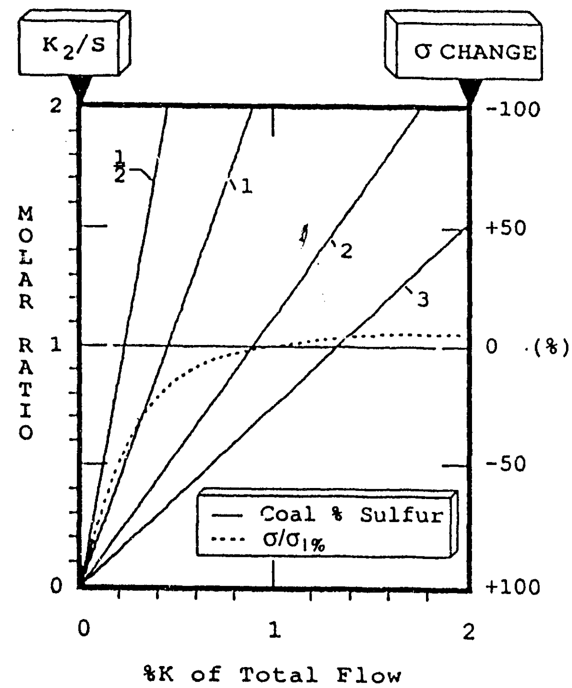

Figure 2. Variations of Conductivity and K_2/S with Seed Fraction

A large turn up/down of the MHD power requires that major changes in operation of the MHD cycle be made. There are possible means of achieving this, i.e.;

1) increase/decrease the magnetic field intensity,
2) modify the MHD generator load setting,
or, 3) increase/decrease throughput,

Item 3 will turn up/down the whole plant while items 1 and 2 affect only the MHD output. All three variations drive the MHD cycle off design and each has advantages and disadvantages. To determine which means is the most appropriate for practice requires consideration of their impact on the overall plant.

A commercial MHD plant will use a large, superconducting magnet. Consideration should be given to the operating procedures for the magnet prior to resetting the field. Superconducting magnet transients are not suited for fast reactions (electrical fault). In fact, magnet operating requirements may be that any change in operation of the magnet is not allowable.

The response of the MHD topping cycle to turn up/down is dependent upon physical and operational design features of the generator. These include physical size, the magnetic field intensity, load configuration, throughput, and Mach number. An MHD generator of a rigidly fixed physical design will perform optimumly at only one operating condition. This fact is the principal one that limits the ability to turn down/up the MHD cycle efficiently.

The performance of the generator is described in terms of the power density, the enthalpy extraction and its length. These measures can be gauged by the following key scaling parameters:

$$\text{Power Density, } P_d \sim \sigma u^2 B^2$$

$$\text{Enthalpy Extraction, } h_{ex} \sim \frac{\sigma u B^2}{\rho}$$

and,

$$\text{MHD Interaction Length, } L_p \sim \frac{p}{\sigma u B^2}$$

where B is the magnetic field intensity. All of these parameters are functional dependent upon the plasma properties in the expanded state; conductivity (σ), velocity (u), density (ρ), and pressure (p). These can be considered as fundamental to the MHD process independent of generator configuration or loading.

Figure 3 maps these parameters as functions of Mach number and throughput, computed for coal combus- tion. Total flow is normalized to throat area to provide insight on system size - each parameter is normalized with respect to magnetic field. Power density and enthalpy extraction of the generator maximize and its interaction length minimizes, for operation at high Mach number.

The plots of Figure 3 show turn up/down of the generator as either a shift in the abscissa scale (loading, magnetic field) or a shift from one throughput curve to another. For a fixed generator geometry, this shift occurs along a vertical, Mach number line. As mass flow increases, power density and enthalpy extraction will decrease - (this is a pressure effect). Interaction length increases with increased flow. Interaction length is a scale by which the required generator length can be interpreted.

One point to be made is that changing the generator length to optimize turn up/down is physically impossible. Turn up/down should be by combined adjustment of flow rate, loading or magnet field to contain operation efficient and consistent with the physical length of the generator. Otherwise, either too much or too little total pressure will exist in the exit flow to maintain the desired flow regime or to allow for efficient diffuser pressure recovery.

Another aspect that these curves suggest is the benefit of variable Mach number operation. Figure 4 gives variations in scaling parameters along lines of constant Mach number for thermal input change. This figure is a composite of Figure 3 encompassing supersonic operation. Normal turn up/down for fixed load and magnetic field appears on this chart a movement from the design point along a constant Mach number line.

With flexibility to control generator Mach number, turn up/down could achieve any given point on the Figure 4

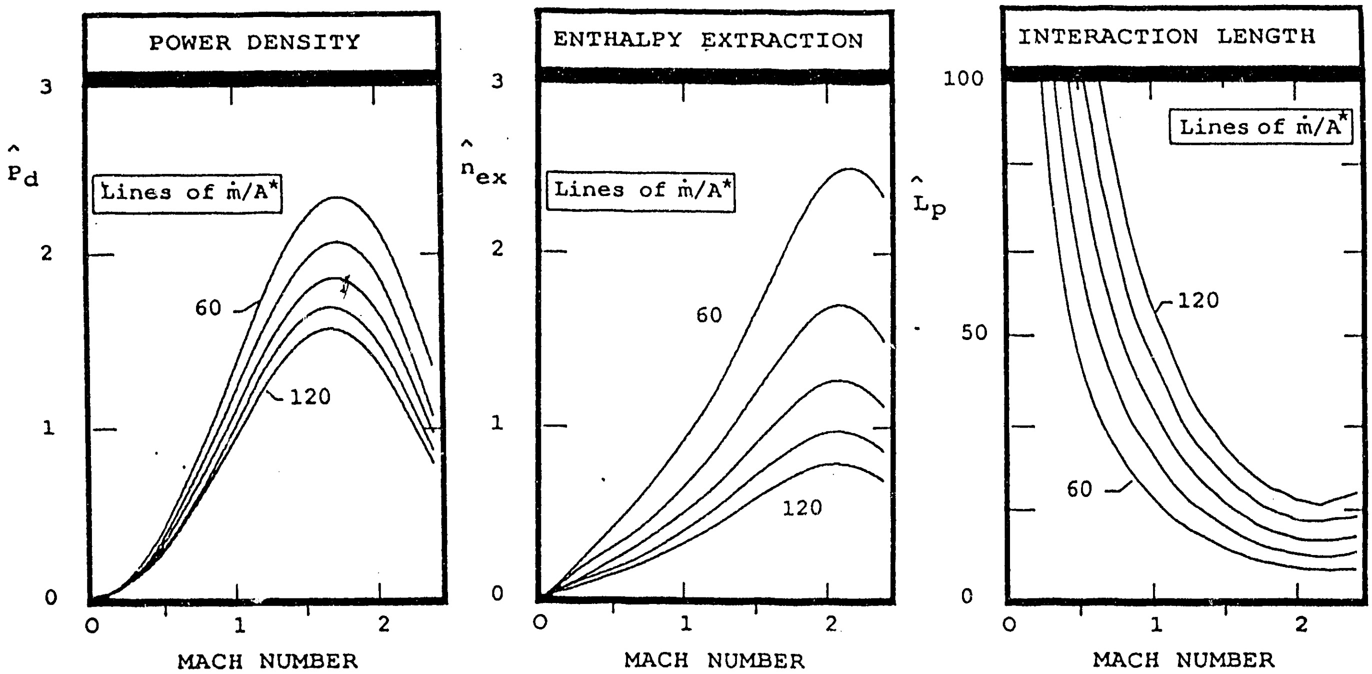

Figure 3. Variations of Generator Performance Parameters with Mach Number and Throughput

chart. One scenario of interest is turn up/down along a constant line of interaction length. By moving horizontally across the condition, the interaction length is maintained consistent with design. A shift in Mach number occurs from the design point to the desired turn up/down end condition. Power density and enthalpy extraction shift for optimum operation over a generator fixed length.

<u>Plant Throughput</u>. Following normal plant practice, large turn up/down of the plant is by adjustment of plant throughput/thermal input. Throughput change will impact MHD plant operation through the MHD process; i.e.,

- combustion pressure will change,
- MHD interaction will change,
- irreversible wall losses will change,

The first of these changes the driving pressure of the system while changing compressor power needed. The second two influence the MHD process in terms of power production, pressure and heat losses. How the overall plant efficiency response when all aspects of turn up/down of throughput is considered is complex .

Mass flow adjustment in either a subsonic or supersonic generator is further limited by the need to control the flow regime. A view of this is provided in the sketch of Figure 5. This sketch represents an MHD generator designed for operation in the transonic range.[6] The flowfield, defined by any point on this figure, is dependent upon interaction and throughput. If either substantially changed, major change in the flow field can occur.

Bound lines constructed on Figure 5 show critical flow situations. Movement of the operating point by changing

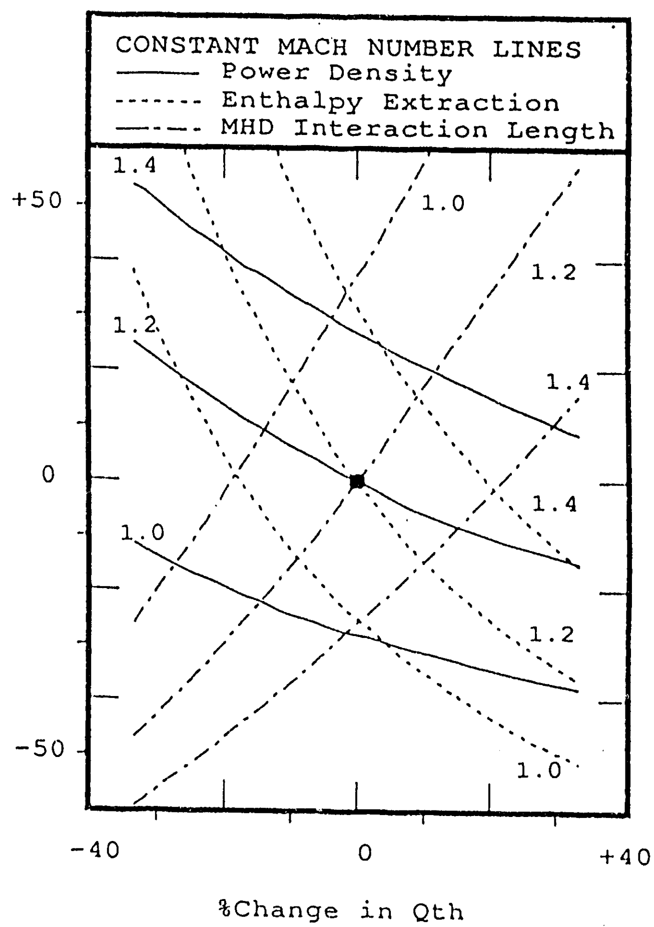

Figure 4. MHD Process Variations with Throughput/Thermal Input

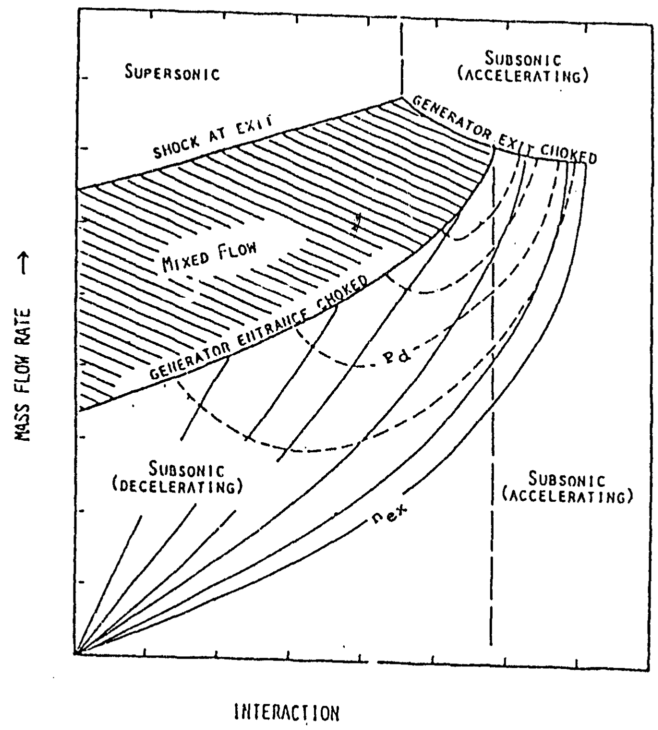

Figure 5. MHD Flowfield Operating Regimes

flowrate or interaction, or both, can force the flowfield into a mixed regime which positions a shockwave in the generator. Alternatively, an MHD throat can be forced. The effects of mixed flow on generator performance and operation are not well understood, especially shock effects.

Conceptual designs for early commercial MHD retrofit plants have selected supersonic operation. A shockwave in the generator should have little affect on operation and MHD performance when the channel is designed for low supersonic operation. Shock losses in the transonic range, below a Mach number of 1.2, are slight and of the same order as shear losses. The transonic channel will be sensitive to turn up/down from the vantage point of MHD induced choking. High mach number generator channel designs will be most likely limited in turn up/down by shock development.

SUMMARY

The intent of this study was to provide a possible initial staging point where renewed study of MHD plant turndown/up needs might begin. New studies should be cast in the light of the plans for development of MHD power as they now exist. This work has emphasized the need for "fresh" thought on this topic. In this context, several areas were stressed:

- the need for new research on problems of MHD plant topping and bottoming cycle integration,
- the need for independent experimental MHD research on the two cycles to coordinate from the perspective of eventual cycle integration,
- the need for research to evaluating part load and transient characteristics of the MHD generator,

and,
- the need to look at advanced MHD generator concepts to broaden the efficient operating range of the MHD cycle around its design point.

None of the candidate means for reducing MHD power that were discussed herein offered a single, comprehensive solution for plant part load operation. It is the opinion of the authors that in the final commercial MHD plant procedures will have to be drawn. Part load operation of the MHD cycle will have to be "tuned in"

Finally, the MHD plant should not be judged more stringently than the steam cycle. Efficiency penalty with turn down exists in the steam plant. Tradeoff studies need to be done to determine just what is what. That is, where is the breakeven point in turn down between the MHD plant and the steam plant in terms of overall plant efficiency.

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